

Higgsstrahlung from R -hadrons

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Abstract

If R hadrons are discovered at the LHC, investigation of their properties will be of paramount importance. One important question is how much of the R -hadron mass is due to electroweak symmetry breaking, *i.e.* the coupling of the Higgs to R -hadrons. In this paper we show that in models where the Higgs has a sizable coupling to R -hadrons we can readily observe Higgs production in association with a pair of R -hadrons (“Higgsstrahlung”). This process can be used to distinguish between different models of R -hadrons. It may be the discovery mode of the Higgs for low mass Higgs bosons, and provides a low-background Higgs sample to study $h \rightarrow \bar{b}b$.

I. INTRODUCTION

If there are heavy colored particles that are stable on collider scales, they will form heavy “ R -hadrons.” These will often be electrically charged, and can therefore be observed at colliders as ionizing tracks. Searches for this signal at the Large Hadron Collider (LHC) have already been carried out by the CMS collaboration with 3.1 pb^{-1} of data [1]. If R -hadrons are discovered, measuring their detailed properties will be of paramount importance. One key property is how much of the mass of the R -hadron arises from the coupling to the Higgs field. In this paper we consider associated production of the Higgs with a pair of R -hadrons, or “Higgsstrahlung” from R -hadrons. We show that this process with $h \rightarrow \bar{b}b$ is readily observable at the LHC if the Higgs coupling to R -hadrons is order 1. This can be used to distinguish among a number of well-motivated scenarios that lead to R -hadrons. For example, if the R -hadron is made of a stop LSP or new heavy colored matter fields we expect sizable Higgs couplings, while if it is a gluino [2–7] we do not.

This paper is organized as follows. In Section 2 we motivate and describe the model we will use as a benchmark for our study. In Section 3, we describe the search strategy. Section 4 gives our conclusions.

II. BENCHMARK MODEL

We now describe a specific model that motivates the signal we will study. We assume that the hierarchy problem is solved by supersymmetry (SUSY). The main problem in SUSY is the Higgs mass is generally too light without fine tuning. In the minimal supersymmetric Standard Model (MSSM) the Higgs mass can be raised above the tree-level bound of $m_Z \cos(2\beta)$ by radiative corrections from the stop sector, but this is generally fine-tuned. One simple way to address this is to assume the existence of additional matter fields with large Higgs couplings. These can raise the Higgs mass with reduced fine-tuning [8–12]. Gauge coupling unification suggests that these extra particles come in complete $SU(5)$ representations, so some of them will be colored. These new colored particles must have highly suppressed mixing to ordinary quarks with the same gauge quantum numbers, which can be made natural with an approximate \mathbb{Z}_2 symmetry under which the new particles are odd. If the new colored particles are stable on cosmological time scales, they are ruled out by direct

searches for heavy stable particles in sea water [13, 14].¹ However, the \mathbb{Z}_2 symmetry may be broken by effects suppressed by high scales such as the GUT scale, in which case the new colored particles will be stable on collider scales without cosmological problems.

As a specific example, we use the QUE model described in Ref. [12]. The new fields come in a $\mathbf{10} \oplus \bar{\mathbf{10}}$ of $SU(5)$ and are denoted $Q, U, E, \bar{Q}, \bar{U}, \bar{E}$. The superpotential is

$$W = M_Q Q \bar{Q} + M_U U \bar{U} + M_E E \bar{E} + \kappa_U H_u Q \bar{U} + \tilde{\kappa}_U H_d \bar{Q} U. \quad (1)$$

The vectorlike masses $M_{Q,U,D}$ can arise by the same mechanism that generates the μ term, and are therefore naturally of order a TeV.

As written, the theory has a global $U(1)$ symmetry that forbids transitions between these new particles and ordinary quarks and leptons. If this symmetry is exact, the lightest of the colored particles Q, U, \bar{Q}, \bar{U} is absolutely stable and forms an R -hadron. (The heavier ones can decay weakly to the lighter ones.) As discussed above, this $U(1)$ symmetry may be naturally broken by small effects, so that the long-lived particles are stable only on collider scales.

Assuming large $\tan \beta$, the largest correction to the physical Higgs mass comes from U , and is given by

$$\Delta m_{h^0}^2 = \frac{N_c}{4\pi^2} \kappa_U^4 v^2 \sin^4 \beta \log \frac{M_S^2}{M_F^2}, \quad (2)$$

where $M_F = M_U = M_Q$ is the U fermion mass and $M_S^2 = M_F^2 + \tilde{m}_U^2$ is the scalar mass. A positive contribution to the Higgs mass requires $M_F < M_S$, and therefore the R -hadrons are made of the fermions. The Yukawa coupling of the new fermions to the physical Higgs boson is approximately

$$y_U = \frac{\kappa_U}{\sqrt{2}} U_{Q1} V_{\bar{U}1}^\dagger \sin \beta, \quad (3)$$

assuming that the physical Higgs is aligned with the Higgs VEV. U_{Q1} is the mixing angle between the lightest mass eigenstate and Q and $V_{\bar{U}1}$ is the mixing between the lightest mass eigenstate and \bar{U} . For $M_Q = M_U$, $U_{Q1} V_{\bar{U}1}^\dagger \sim \frac{1}{2}$ for $M_F \gg \kappa_U v \sin \beta$.

What value should we expect for κ_U ? There is a contribution to the Higgs mass parameter that goes as $\sim \kappa_U^2 M_0^2$, so avoiding fine tuning favors large κ_U . The Yukawa couplings $\kappa_U, \tilde{\kappa}_U$

¹ These bounds do not apply if the universe has a low reheating temperature, so that the new particles are not thermally produced. Such a scenario requires low-temperature mechanisms to explain the baryon asymmetry and origin of dark matter.

must be $\lesssim 1.05$ to avoid Landau poles below the GUT scale [12]. However, larger values of the Yukawa coupling are not necessarily incompatible with gauge coupling unification, since it is plausible that the new particles can be composite at some scale below the GUT scale. Because these states form a complete GUT multiplet, the composite dynamics need only be invariant under $SU(5)$ in order to be compatible with unification.

III. THE HIGGSSTRAHLUNG SIGNAL

The 7 TeV LHC is expected to gather 5 fb^{-1} per experiment, and should be able to discover R -hadrons with mass up to approximately 800 GeV. In the event of a discovery, the next task is to understand the properties of the R hadrons in order to determine how they fit into a larger theory. One important clue is the coupling of the Higgs to the R -hadrons. This will be large if the R -hadrons get a sizable contribution to their mass from the Higgs VEV, or equivalently large radiative corrections to the physical Higgs mass come from the R -hadrons. It is also possible for the R -hadron mass to preserve electroweak symmetry, for example a gluino in supersymmetry. Observation of Higgs production in association with R -hadrons (“Higgsstrahlung”) directly measures the coupling of R -hadrons to Higgs bosons. This provides a very clean sample of Higgs bosons, since R hadrons have no standard-model backgrounds. The only background to the Higgsstrahlung process is QCD jets produced in association with the R hadron. We focus on light Higgs bosons decaying to $\bar{b}b$, and show that simple jet cuts and a single b tag are sufficient to reduce the R -hadron plus jets background to low levels. Depending on the R -hadron mass, this can be a discovery mode for a light Higgs boson at the 7 TeV LHC, and provides a clean sample of Higgs bosons to study $h \rightarrow \bar{b}b$.

We simulated $\bar{U}U h$ production in MadGraph [15]. Parton-level $\bar{U}U h$ and $\bar{U}U h j$ were combined to produce a signal sample with up to one additional hard jet. We performed a parton-level analysis with a Gaussian smearing of the jets using the function [16]

$$\frac{\sigma(E_T)}{E_T} = \frac{a}{E_T} \oplus \frac{b}{E_T} \oplus c, \quad (4)$$

for $(a = 5.6, b = 1.25, c = 0.033)$ when $|\eta| < 1.4$ and $(a = 4.8, b = 0.89, c = 0.043)$ when $1.4 < |\eta| < 3.0$. We used an assumed b -tagging efficiency of 0.3. Backgrounds were simulated using AlpGen [17]. We analyzed both the 7 TeV LHC and the 14 TeV LHC. In both cases,

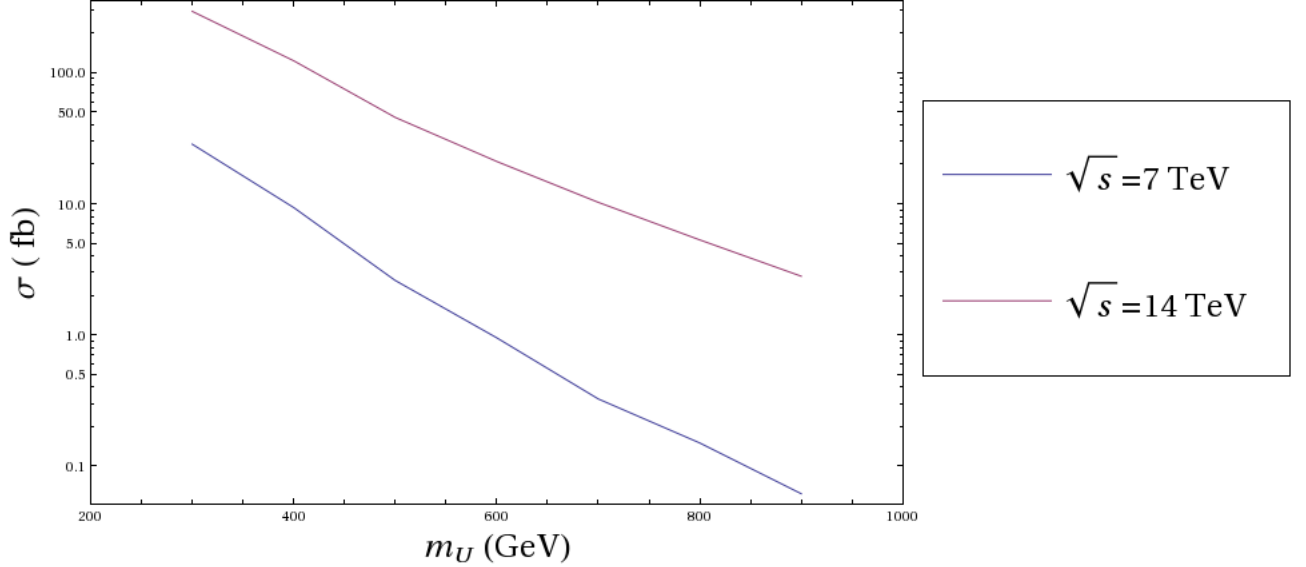


FIG. 1: The cross section for $\bar{U}U h$ production for $m_h = 115$ GeV at the 7 TeV and 14 TeV LHC.

we use $y_U = 1/\sqrt{2}$ in Eq. (3), roughly the largest value consistent with perturbative coupling constant unification. Increasing this coupling will improve the situation. The cross section for $\bar{U}U h$ production at the LHC is shown in Figure 1 for $m_h = 115$ GeV for the 7 TeV and 14 TeV LHC.

A. 7 TeV LHC

CMS has searched for highly-ionizing tracks from R -hadrons with 3.1 pb^{-1} of 7 TeV data [1], and for stopped late-decaying R -hadrons using 10 pb^{-1} of data [18]. These searches are quite model-independent, and set a lower limit $\gtrsim 275$ GeV. We will therefore be interested in R -hadrons with masses in the range 300 GeV to 1 TeV.

For our search it is critical to identify the particles produced in association with the R -hadron, so we focus on searches with highly ionizing tracks. An important question is the efficiency with which the R -hadrons will be tagged and reconstructed. In our benchmark model the U quark has the same color quantum numbers as the stop, one of the particles searched for in the CMS search. We expect that our R -hadrons will hadronize in roughly the same way (given the large theoretical uncertainties in the hadronization), so we estimate the efficiency by comparing with stops. The efficiency is most sensitive to the β of the produced

	Signal	Background
R -hadron + 2 jets with $p_T > 50$ GeV, $ \eta < 2.5$	6.2 fb	220 fb
≥ 1 b -tag	3.2 fb	2.2 fb
Higgs mass window ± 25 GeV	2.5 fb	0.37 fb

TABLE I: Signal and background rates for $m_U = 300$ GeV and $m_h = 115$ GeV at the 7 TeV LHC.

R -hadrons. We have checked that the β distribution for R -hadrons produced in association with a Higgs is similar to the β distribution for pure R -hadron production in the relevant range $\beta \lesssim 0.6$ where the search is sensitive. For stop masses ranging from 300 GeV to 1 TeV the efficiency to find an event with two R -hadrons at CMS is $\simeq 0.2$, so we assume this value for our signal efficiency.

In addition to the R hadron, we require at least 2 jets, each with $p_T > 50$ GeV and $|\eta| < 2.5$. We then require that at least one of these jets have a b -tag. We use the events passing these cuts to form an estimate of the Higgs mass. In events with 2 b -tagged jets we use these to form the invariant mass, otherwise we combine the b -tagged jet with the remaining jet with the highest p_T . In a model with $m_U = 300$ GeV, we show the effect of these cuts on signal and background in Table I. In this model, there are plenty of events to see a Higgs mass peak, as shown in Fig. 2. For 10 fb^{-1} we estimate $S/\sqrt{B} \simeq 13$ for the Higgs mass peak defined by $m_h \pm 25$ GeV. This will be diluted by a trials factor for Higgs discovery, but it illustrates that a significant Higgs discovery can be made early in this channel.

B. 14 TeV LHC

The 14 TeV LHC is expected to be sensitive to R -hadron masses up to about 2 TeV [19]. We assume that the signal acceptance for R -hadrons is the same as the 7 TeV LHC, *i.e.* 0.2. For the increased energy, the background increases at a faster rate than the signal due to the increased p_T of the jets. This gives a modest increase to the size of the background relative to the signal, however, S/B can still be made larger than 1. We find that the discovery reach for this process is rate limited, and we can conservatively hope to probe $m_U < 800$ GeV in the case of $m_h < 125$ GeV with 100 fb^{-1} of data. Table II gives an example of the

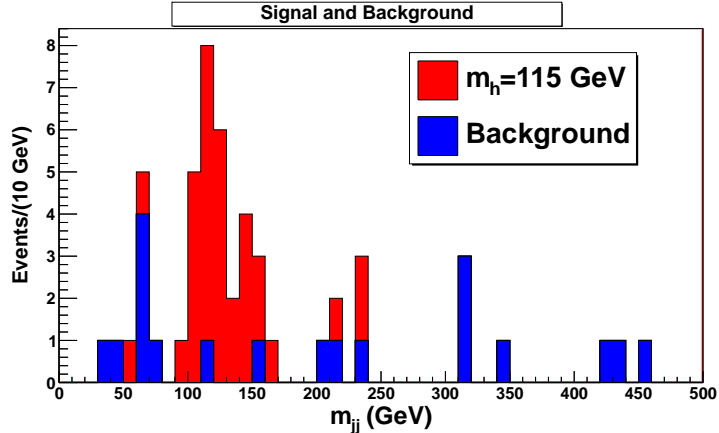


FIG. 2: 10 fb⁻¹ of simulated data for the 7 TeV LHC with $m_U = 300$ GeV and $m_h = 115$ GeV, using cuts described in the text.

	Signal	Background
Cross section requiring R -hadrons and $h \rightarrow \bar{b}b$ or 2 jets	8.9 fb	820 fb
Requiring at least 1 b-tag	4.5 fb	9.5 fb
Requiring 2 jets with $p_T > 50$ GeV and $\eta < 2.5$	2.2 fb	3.2 fb
In mass window $m_h \pm 25$ GeV	1.5 fb	0.42 fb

TABLE II: Example numbers for $m_U = 500$ GeV and $m_h = 115$ GeV at the 14 TeV LHC.

signal cross section after basic cuts, and Figure 3 shows the signal for these same cuts with 100 fb⁻¹ of data.

IV. CONCLUSION

In this paper we explored the ability of the LHC to discover the Higgs in associated production with R -hadrons. We found that for a wide range of R -hadron masses discovery is possible. If R -hadrons are discovered in the first stage of running at the LHC, a more careful study should be undertaken to determine the reach of the LHC for associated Higgs production. This can determine if a significant part of the R -hadron mass arises from electroweak symmetry breaking, and therefore distinguish between different models of R -hadrons. Additionally, it gives a potential clean channel to study $h \rightarrow \bar{b}b$.

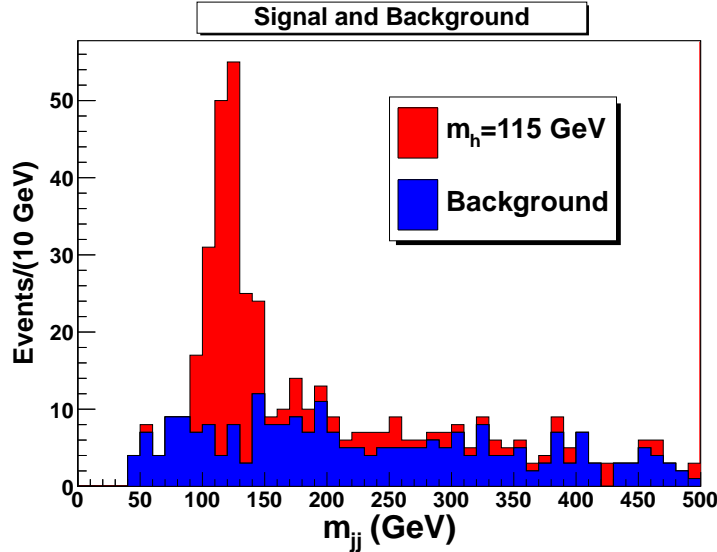


FIG. 3: 100 fb⁻¹ of simulated data for the 14 TeV LHC with $m_U = 500$ GeV and $m_h = 115$ GeV, using cuts outlined in Table II.

Note added: While this work was underway, we learned of independent work by S. Chang, C. Kilic, and T. Okui that considers similar questions [20].

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